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During winters, the northern Adriatic Sea experiences frequent, intense cold-air outbreaks that drive oceanic heat loss and imprint complex but predictable patterns in the underlying waters. This strong, reliable forcing makes this region an excellent laboratory for observational and numerical investigations of air-sea interaction, sediment and biological transport, and mesoscale wind-driven flow.

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Northern Adriatic Response to a Wintertime Bora Wind Event

During winters, the northern Adriatic Sea experiences frequent, intense cold-air outbreaks that drive oceanic heat loss and imprint complex but predictable patterns in the underlying waters. This strong, reliable forcing makes this region an excellent laboratory for observational and numerical investigations of air-sea interaction, sediment and biological transport, and mesoscale wind-driven flow.

Narrow sea surface wind jets, commonly known as "bora," occur when cold, dry air spills through gaps in the Dinaric Alps (the mountain range situated along the Adriatic's eastern shore). Horizontal variations in these winds drive a mosaic of oceanic cyclonic and anticyclonic cells that draw coastal waters far into the middle basin. The winds also drive intense cooling and overturning, producing a sharp front between dense, vertically homogenous waters (North Adriatic Dense Water, or NAdDW) in the north and the lighter (colder, fresher), stratified waters of the Po River plume. Once subducted at the front, the NAdDW flows southward in a narrow vein following the isobaths (contours of constant depth) of the Italian coast. In addition to governing the basin's general circulation, these processes also influence sediment transport and modulate biological and optical variability.

Building on a long history of scientific investigations [*Cushman-Roisin et al.*, 2001], scientists from several countries conducted intensive multi-disciplinary studies of the northern and central Adriatic during 2002 and 2003. The U.S. Office of Naval Research, NATO, the Croatian Ministry of Science and Technology, and the Italian Ministry of the Environment and Ministry of Universities and Research supported large observational and numerical modeling programs.

The Dynamics of Localized Currents and Eddy Variability in the Adriatic (DOLCEVITA) program investigated the mesoscale and submesocale response to strong atmospheric and riverine forcing within the context of large-scale circulation studies conducted by the Adriatic Circulation, West Istria, and East Adriatic Coastal Experiments (ACE, WISE, EACE). European Margin Strata Formation (EUROSTRATAFORM) investigators worked to understand how sediment transport processes produce observed deposition patterns off the Po and Apennine river systems.

The Mucilage Adriatico-Tirreno (MAT) project conducted monthly physical and biological measurements along three northern Adriatic sections, while other studies focused on bottom-layer hypoxia. The Adriatic Sea Integrated Coastal Area and River Basin Management System (ADRICOSM) pilot project employed measurements and extensive modeling to establish a near-real-time forecast system. High-resolution ocean and atmosphere simulations conducted by the U.S. Naval Research Laboratory supported many of the projects.

The combination of these large, multi-investigator programs and numerous smaller efforts provide a unique, multi-faceted view of the northern Adriatic. Measurements included half-year moored time series at several locations, extensive surface drifter deployments, coastal high-frequency radars, regular hydrographic surveys, high-resolution towed profiler surveys during bora events, microstructure profiles, remote sensing (advanced very high resolution radiometer (AVHRR), ocean color,

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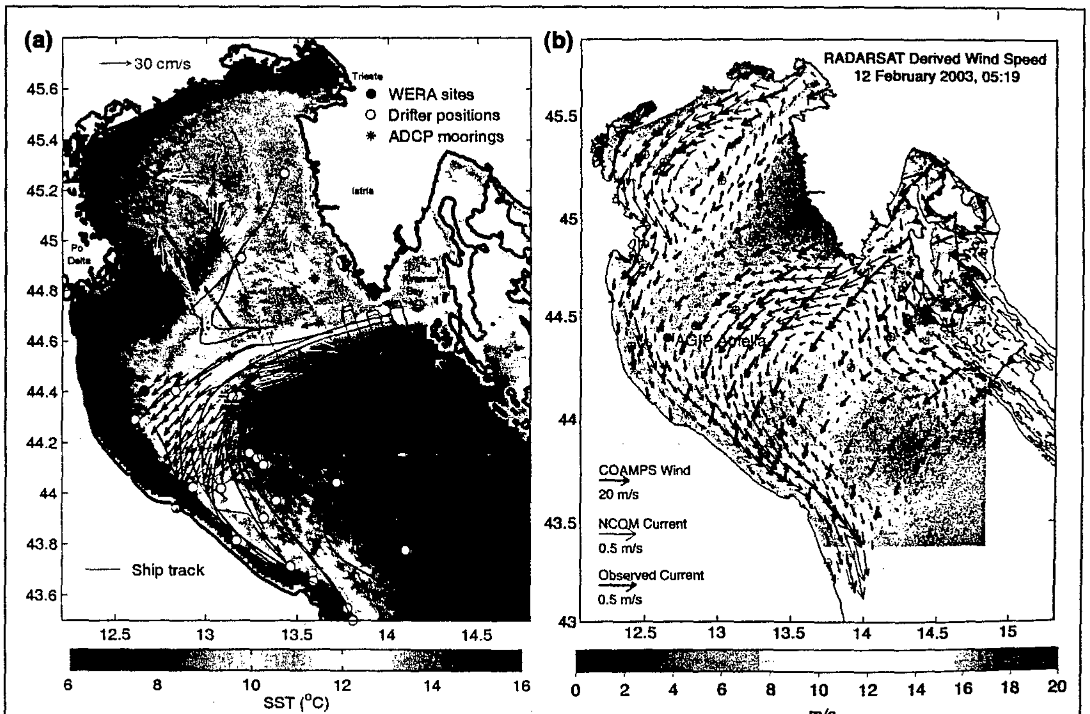

Fig. 1. (a) Nine-day mean AVHRR sea surface temperature with current vectors and drifter tracks illustrating many of the observations collected during the 11–19 February 2003 bora. Gray lines mark part of the R/V Knorr *cruise track, with white arrows showing 12-m velocity measured from the shipboard acoustic Doppler current profiler (ADCP). Black lines trace drifter tracks, with white circles marking locations at the end of this period. Black asterisks and arrows indicate near-surface, 9-day mean velocities measured by bottom-mounted ADCPs and current meter moorings. The field of black arrows between 44°N and 44.4° N depicts the 9-day mean surface velocity field measured by two Wave Radar (WERA) high-frequency coastal radars (located on the Italian coast at the red circles). A black dot marks the AGIP Amelia platform, and a magenta line marks the location of the section shown in Figure 2. All velocity vectors are scaled according to the red vector in the upper left corner. (b) RADARSAT wind speed (color) on 12 February with 48-hour average (12–14 February) Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) wind vectors (black), near-surface (5 m) Navy Coastal Ocean Model (NCOM) currents (green), and measured currents (magenta). A magenta circle marks the AGIP Amelia platform. The 4 km (1 km) COAMPS (NCOM) vectors are shown at 16 km (6 km) intervals for clarity. Large-scale bora winds from the northeast are intensified by coastal topographic gaps into sea surface wind jets that can extend across most of the Adriatic.*

By C. M. Lee, F. Askari, J. Book, S. Carniel, B. Cushman-Roisin, C. Dorman, J. Doyle, P. Flament, C. K. Harris, B. H. Jones, M. Kuzmic, P. Martin, A. Ogston, M. Orlic, H. Perkins, P.-M. Poulain, J. Pullen, A. Russo, C. Sherwood, R. P. Signell, and D. Thaler Detweiler

Bora

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cold, fresh waters of the front's north side.

The absence of a near-bottom suspended particulate maximum suggests that these high concentrations were not produced by local resuspension, but may instead have been advected from the region surrounding the coastal islands to the east and southeast. The physical and bio-optical variables were highly correlated on either side of the front, indicating that the physical processes dominated the distributions of the bio-optical properties.

Sediment Transport

Bora winds affect sediment distribution by enhancing waves and strengthening currents. The Po River in the north and small, episodically flooding rivers that drain the Apennine Mountains to the Adriatic central basin are the major sources of sediment. Though most Po River sediment appears to settle on the bed within hours of reaching the coastal sea, much is redistributed before ultimately being buried. Transport within the bottom boundary layer (~10 m thick) usually dominates sediment flux. Although sediment flux variability is high, on average bora events drive sediment southward along the shelf with little across-shelf transport.

The 11–19 February bora produced sediment transport patterns consistent with larger bora events on record. Elevated sediment concentrations measured at sites along the Italian coast are associated with waves generated during bora events (Figure 3). Wave heights on the Po delta reached approximately 1.1 m, with peak suspended-sediment concentrations approaching 0.5 g/L at 30 cm above bottom (Figure 3).

Between 15 and 19 February, net sediment flux on the Po delta was dominated by a 22-hour period when the currents were consistently southward, along the bathymetry. Although sediment concentrations were equally high during the rest of the bora period, fluctuating current direction produced little net flux.

Synthesis Provided by Numerical Results

Several groups conducted high-resolution ocean (2 km), atmosphere (4 km), and sediment transport simulations that provide critical tools for assessing Adriatic dynamics. Counter-rotating gyres, cyclonic in the far north and anticyclonic nestled against the Istrian peninsula, are a generic response to bora forcing that strongly affects the biology and sediment (Figure 1b). The gyres help maintain frontal boundaries and drive cross-basin transport. The WAC acts as a conduit for riverine waters and sediment. A paucity of observations impedes the understanding of small-scale circulation along the Croatian coast, although these features may participate in wintertime dense water formation. The cyclonic gyre located off the Po mouth transports a small, but noticeable fraction of sediment to the northeast (not shown).

Modeled wave orbital velocities and sediment concentrations capture the dynamics of bora-induced transport (Figures 3b and 3c). Model results for the 9-month winter period show that several mechanisms contribute to southward alongshore sediment transport in a narrow coastal band in the western Adriatic. These include buoyancy-induced coastal flow associated with river-derived sediments, wind-enhanced coastal flow coupled with wave-resuspended sediments under both strong winds, and persistent counter-clockwise flow driven by basin-scale estuarine circulation and mean wind stresses. In these simulations, these mechanisms produced depositional patterns similar to the observed late Holocene deposits, suggesting that event scale models can provide insight about sedimentation on geologic timescales.

The unprecedented suite of research activities that focused on the Adriatic in winter 2003 provided a multi-faceted view of bora events and the resulting oceanic response. Observational and numerical efforts spanned a broad range of temporal and spatial scales, providing a "four-dimensional" (space and time) depiction of bora response that will facilitate detailed dynamical investigations of response to small-scale wind forcing, dense water formation, and Adriatic general circulation. Likewise, multi-disciplinary measurements and modeling promise to characterize the biological and sediment response to bora-induced dynamics.

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